Nonlinear magnetoelastic waves in thin iron borate platelets

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A slow nonlinear magnetoelastic wave has been observed experimentally in iron borate. This wave can be visualized by a magnetooptic technique. It has a transverse corrugation structure whose period depends on the magnetic field.

Magnetoelastic waves in weak ferromagnets such as hematite and iron borate have been the subject of many studies and systematic reviews.[1,2] Because of the strong magnetoelastic coupling in these compounds, they hold promise for the observation of nonlinear effects and magnetoacoustic solitons.[2] Experiments aimed at the visualization of magnetoacoustic solitons are important for proving the existence of such solitons. The reviews cited above contained no results on the visualization of magnetoelastic waves. In this letter we report the first experimental results on an unusually slow nonlinear magnetoelastic wave in iron borate and on the visualization of this wave by a magnetooptic technique.

The experiments were carried out on thin iron borate ($FeBO_3$) platelets with a thickness of 30–90 μm and a large basal plane. The end of a glass rod was pressed through a thin coating of oil against one end of the platelet. This rod served as an acoustic damper or buffer. A longitudinal-sound piezoelectric transducer with a resonant frequency of 3.4 MHz was cemented with phenyl salicylate to another end. The transducer was driven by a video voltage pulse with a height up to 1.6 kV and a length ≈ 160 ns. The sound pulse was 1.5–2 μs long. The measured strain in the test crystal reached 3×10^{-5}.

A slow acoustic wave was observed when a sound wave was applied to a sample magnetized uniformly by a weak magnetic field (a few oersteds) directed perpendicular to the wave vector. The wave was observed by a high-speed photographic technique with pulsed illumination by an oxazole-dye laser with a wavelength of 535 nm pumped by a nitrogen TEA laser with a pulse length of 0.3 ns (Ref. 3). The observation technique made use of the Faraday effect in the platelet, which was inclined at an

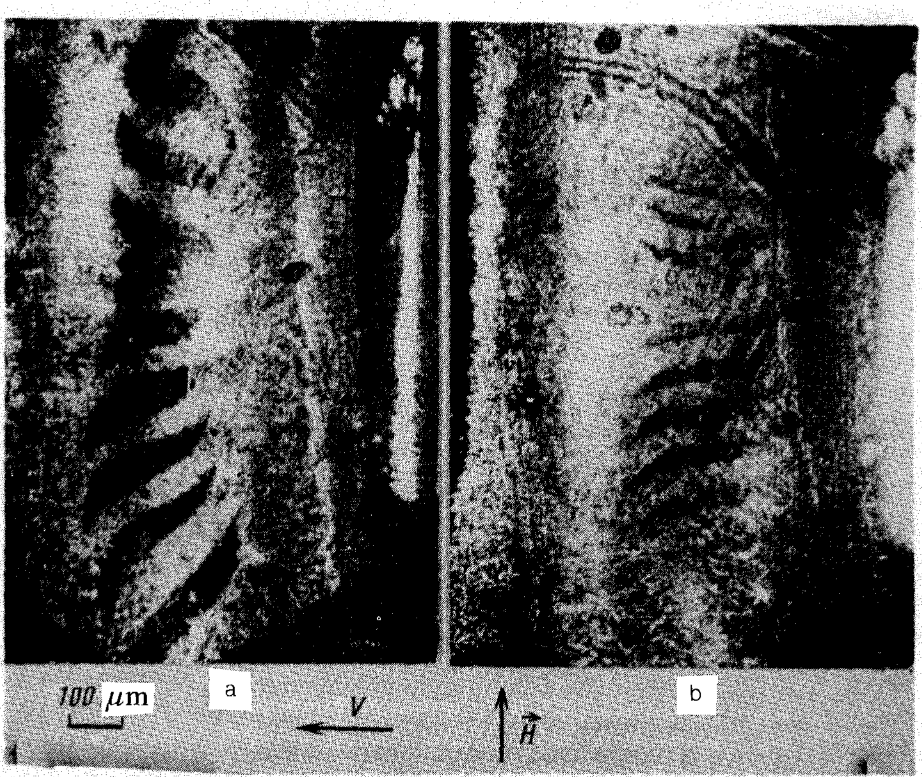

FIG. 1. Nonlinear magnetoelastic waves in iron borate in magnetic fields $H\perp\mathbf{K}$ of two strengths. *a*—$H=1$ kOe; *b*—5 Oe. The waves were visualized through the use of the Faraday effect.

angle $\approx 10^\circ$ with respect to the horizontal axis and a few degrees with respect to the vertical axis, so that there would be magnetization components along the light propagation direction.

With no voltage on the transducer, the rotation of the polarization plane in a uniformly magnetized sample amounted to $\approx 1^\circ$. At transducer voltages up to that corresponding to a strain $\approx 10^{-6}$ in the sound wave, no change was observed in the uniformity of the rotation of the polarization plane over the entire sample. The sample was broken up into several alternating bright and dark bands with diffuse, poorly defined boundaries running perpendicular to the wave vector. These bands moved at 1.8 ± 0.2 km/s.

With a further increase in the voltage on the transducer, to a sound amplitude $\geqslant 10^{-5}$, the boundaries between these bands became sharper, and a strictly periodic, steady-state domain structure appeared in every other band, in the direction transverse with respect to the wave vector (Fig. 1). The structures moved as a whole at the same velocity (within the indicated error). The application of a magnetic field H along the wave propagation direction caused the dark regions to grow, and the bright ones to shrink. A reversal of the field direction had the opposite effect. In the dark regions the dynamic magnetization structure is thus close to the direction of the wave motion, while that in the bright regions it is in the opposite direction.

The closure of the magnetic flux at the wavefront occurs through the domain ahead of the structure. How the magnetic flux closes behind the structure is not yet clear. It is possible that other layers of the sample, parallel to the basal plane and

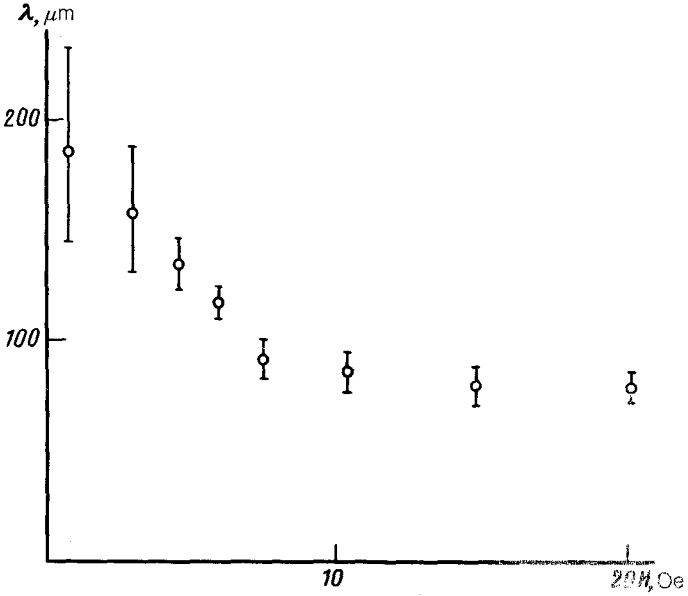

FIG. 2. Period of the magnetoacoustic wave versus the strength of a magnetic field $H \perp \mathbf{K}$.

separated from each other by Bloch domain walls, are involved. It may be that there is no flux closure behind the nonequilibrium dynamic structure.

When the magnetic field is directed transverse with respect to the wave vector **K**, the period of the structure decreases. Figure 1b shows photographs of the structure in a magnetic field $H \perp \mathbf{K}$ with a magnitude ≈ 5 Oe. Figure 2 shows the period of the dynamic structure as a function of the amplitude of a field $H \perp \mathbf{K}$. The period falls off smoothly with increasing field. The front of the dynamic structures observed here is similar to the structures which arise at a dynamic domain wall in yttrium orthoferrite and in iron garnets on parts of the curve of the velocity of the wall versus the magnetic field on which there is a negative differential mobility.[3] An increase in the magnetic field above 40 Oe completely erases any structure in the sample, i.e., leads to a uniformly magnetized crystal. This is true for fields oriented either parallel or perpendicular to the sound propagation direction.

The physics of the observed effects can be outlined as follows. The strain accompanying the sound wave alters the local anisotropy constant in the iron borate. The magnitude of this constant in the basal plane is small ($H_a < 0.1$ Oe) and is essentially determined by the external pressure alone.[2] In the extension region, the easy axis of the crystal turns out to be directed along the wave propagation direction. Where the strain in the wave is sufficient to change the sign of the anisotropy constant, a dynamic orientational phase transition occurs. The magnetic moments in the regions in which this transition has occurred are directed along the wave propagation direction (Fig. 3). When the wave amplitude is smaller than the transition amplitude, one observes a smooth distribution of the stain in the wave (i.e., the linear case), as is indicated by the absence of clearly defined boundaries in the structure in the sample in this case. At high strain amplitudes, the magnetoelastic wave becomes nonlinear, with a sharply defined profile and with a clearly expressed transverse undulation of the structure in it. We do not rule out the possibility that Lighthill's condition for a modulational instability is satisfied under these conditions. The unusually low velocity of the nonlinear

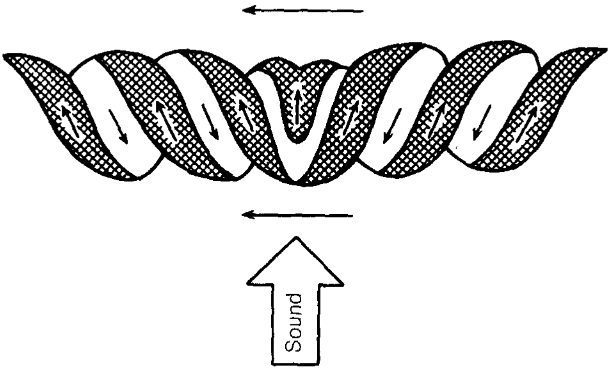

FIG. 3. Arrangement of magnetic moments in the dynamic domains of a nonlinear magnetoelastic wave. The direction of the fields applied in the experiments was in the plane of the sample (or that of the figure), either perpendicular or parallel to the sound propagation direction. The z axis is perpendicular to the plane of the figure.

magnetoelastic wave deserves mention. This velocity is smaller by a factor of 5 than the longitudinal sound velocity in an unbounded sample.[2] Measurements have shown that this velocity is smaller by a factor of at least 3 than the velocity of this sound in a thin iron borate platelet (≈ 6 km/s) at the frequency stated above. It is possible that this wave stems from Lamb waves.

A theory for the observed effects should be based on a joint solution of the equation of motion of the magnetic moment and the elastic wave. The strong magnetoelastic coupling should be taken into account. Dynamic (band) structures associated with longitudinal sound in easy-plane ferromagnets have been studied by Shavrov and Kabychenkov.[5] It is possible that the results derived by Turitsin and Fal'kovich[6] might prove useful in interpreting the nonlinear case. Those authors demonstrated theoretically that there can be a transverse undulation of a magnetoelastic soliton as it propagates through an easy-plane magnetic material at a velocity which might be considerably lower than the longitudinal sound velocity.

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